EXPERIMENTAL METHODS IN BUILDING ACOUSTICS FOR EVALUATING THE FLANKING TRANSMISSION

By

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C a p i t u l o 1

Introducción

Todo trabajo científico debe tener, en principio, presupuestos y suposiciones claras que conduzcan a un objetivo más fácil de realizar. En esta línea de pensamiento, el trabajo presente trata de alcanzar y clarificar esos presupuestos y suposiciones. La concepción de edificios así como las técnicas de construcción empleadas deben ser tales que el ruido percibido por los ocupantes se mantenga a un nivel bajo de forma que no amenace su salud ni las condiciones satisfactorias de vida. El confort acústico es, en nuestros días, una de las razones para la satisfacción e integración en la sociedad. Esto tiene más importancia en los países mas desarrollados.

Existen muchos lugares donde la vida normal del ser humano es desarrollada: casa, trabajo, lugares de ocio, etc. Existen así mismo diversas formas de potencia sonora que perturban esos lugares. Sin embargo, si hay un lugar donde la perturbación del sonido no puede llegar a niveles intolerables (confort acústico) es en las viviendas particulares. En nuestros días, es conocido que el sonido puede ser transmitido de una sala a la contigua por vibración estructural o por otros caminos además del elemento de separación entre las salas. Estos caminos indirectos pueden aumentar el nivele de sonido en salas adyacentes bastante más de lo supuesto a hasta hace pocos años atrás. Este trabajo así como los futuros, pretenden ser una contribución más para obtener mejores condiciones acústicas en los edificios y aportar nuevos conocimientos y "savoir faire".a la comunidad científica.

En primer lugar se realizó una búsqueda en las revistas, libros, y artículos especializados en las áreas de conocimiento de acústica de edificios y transmisiones por flancos. La información compilada fue tratada con el fin de resumir y conocer todo el trabajo científico efectuado hasta el momento y ponernos en el centro de la cuestión. Una vez centrado el tema, se han realizado diversas medidas de aislamiento en un edificio de la universidad (medidas *in situ*), con el método de presión y el método de intensidad. Estas medidas fueron entonces tratadas, procesadas, comparadas y discutidas con el fin de cumplir el principal objetivo de este trabajo, que es llegar iniciar un tema de trabajo para la futura tesis doctoral.

C h a p t e r 1

1 - Introduction

All the scientific work must have at the beginning presupposes and assumptions clarified, that could lead to an objective more easily to accomplish. In this line of thought, the present work is to achieve and clarify those presupposes and assumptions. The design of building and his constructions techniques must be built in such a way that the noise perceived by the occupants is kept down to a level that will not threaten their health and satisfactory living conditions. The acoustical comfort is nowadays one of the main issues for the satisfaction and integration on the society. This has more relevance in developed countries.

There are many places where the normal human living is developed: home, work, leaser places, etc, has there are many forms of sound power that disturb those places. However, where the sound perturbation must not reach intolerable levels (acoustical comfort) are in buildings, especially in living buildings. Nowadays is known that sound could be transmitted by structural vibration or by other paths than the separating element of the dwellings. These paths could increase the sound levels of the adjoining rooms with a bigger importance than the supposed a few years ago. The present and future works are more a contribution to obtain better acoustical conditions in buildings and put to the scientific community more knowledge and "savoir faire".

Firstly a search was made in reviews, books and papers specialized in the areas of knowledge of building acoustics and flanking transmission. The information recovered was treated to clarify all the present work done till the moment and to put us in the center of the issue.

Secondly several measurements were performed in an old building of the university (*in situ* measures), by pressure method and intensity method. Those measures were then treated, processed, compared and finally discussed to accomplish the main objective of this work, which is getting an objective theme to the future doctoral thesis.

C a p i t u l o 2

Revisión de la literatura

En este capítulo se hace una compilación bibliográfica y teórica sobre los métodos de medición acústica más utilizados en acústica de edificios relativos al aislamiento sonoro.

En el punto 2.2 se describe el método de presión, tanto para medidas en laboratorios como para medidas in situ. Calculando los aislamientos obtenidos para ambas situaciones.

En el punto 2.3 se describe el método de intensidad, comenzando por esclarecer lo que se entiende por intensidad y después se hace una descripción de cómo se hacen medidas en laboratorio e *in situ*. En los apartados 2.3.1, 2.3.2 y 2.3.3 se da una descripción más detallada de los procedimientos de medida por intensidad y de los cálculos para llegar al índice de aislamiento sonoro por intensidad.

El punto 2.4 hace una comparación entre los métodos de presión e intensidad, con referencia a los aspectos positivos y negativos de cada método. Haciendo también una compilación bibliografiíta de artículos científicos sobre el tema.

El punto 2.5 habla de la frecuencia crítica y su formulación matemática. La influencia de las ondas sonoras cuando inciden en la pared, en particular cuando se trata de construcciones aligeradas, que implica que dicha frecuencia aumente hacia valores muy próximos de las frecuencias de interés en acústica arquitectónica.

C h a p t e r 2

2 - Review of the literature

2.1 Measurement of airborne sound insulation

This section gives a general overview of measurement methods of airborne sound insulation.

2.2 Pressure method

Sound reduction index, *R* is the most usual acoustical quantity determined in laboratory or *in situ* measurements. The first theoretical formulation to determine sound transmission loss between two rooms was presented in the earlier 1920's and the first ASTM standard was proposed in 1951. The principle of this method was remained the same over the years. The present standard is e.g. ISO 140-3 [1] for laboratory measurements or ISO 140-4 [2] for *in situ* measurements.

The sound reduction index, *R* [1], between two rooms, room (1) the source volume and room (2) the receiving volume, separated by a test specimen, is defined by:

$$R = 10\log\frac{1}{\tau} = 10\log\frac{W_1}{W_2} \quad [\mathrm{dB}] \tag{2.1}$$

Where τ is the transmission coefficient and W_1 and W_2 are the incident and transmitted sound powers respectively. The source room is supposed to create a diffuse sound field. Thus, the incident sound power can be determined by the average sound pressure, p_1 [Pa] measured in the source room on a steady-state situation, as follows:

$$W_1 = \frac{p_1^2}{4\rho_o c_o} S \tag{2.2}$$

Where S [m^3] is the area of the test specimen, ρ_o [kg/m^3] is the density of air and c_o [m/s] is the velocity of sound in air. The transmitted sound power is determined, in steady-state conditions, when the sound power radiated in the source room equals the absorbed sound power in the receiving room:

$$W_2 = \frac{p_2^2}{4\rho_o c_o} A_2 \tag{2.3}$$

$$A_2 = 0{,}16 V_2 / T_2 \tag{2.4}$$

Where p_2 [Pa] is the average sound pressure in the receiving room and A_2 [m^2] is the room absorption area of the receiving room. It is estimated by (2.4) the Sabine [1] equation, where V_2 [m^3] and T_2 [s] are the volume and reverberation time of the receiving room, respectively.

Then the sound reduction index, R, using the pressure method is determined by:

$$R = L_{p1} - L_{p2} + 10\log\frac{S}{A_2} \quad [\mathrm{dB}] \tag{2.5}$$

Where, L_{p1} and L_{p2} are the average sound pressure levels in the source and receiving room, respectively. The R is determined indirectly from the average sound levels of the adjacent test rooms.

$$L_{pi} = 10\log\left(\frac{p_i}{p_{ref}}\right) \quad [\mathrm{dB}] \tag{2.6}$$

Where, p_{ref} is 20 [μPa].

The sound reduction index is usually determined in third-octave frequency bands at least in the range 100 to 3150 [Hz] from which the single number presentation, or weighted sound reduction index, R_W, is determined according to ISO 717-1[3].

Eq. (2.3) presupposes that all sound energy is transmitted via the test specimen or wall. In practice the wall, is not the only path, via which sound enters in the receiving room, W_2 is also the contribution of other room surfaces. This is called the flanking transmission and is discussed in section **2.5**.

For the *in situ* measures the *R'* [2] [2] apparent sound reduction index is obtained by

$$R' = 10\log\left(\frac{W_1}{W_2 + W_3}\right) \quad [\mathrm{dB}] \tag{2.7}$$

where W_1 is the sound power in source room and W_2 is the sound power transmitted by the separating element under test, W_3 is the sound power transmitted through flanking elements or by other components.

Background noise levels are measure to ensure that observations in the receiving room are not affected by extraneous noise sound, such noise from outside the test room.

Corrections for background noise are made according to specification of ISO 140-4 [2]. The background level shall be at least 6 [dB] (and preferably more than 10 [dB]) below the signal and background noise combined. If the difference in levels is smaller than 10 [dB] and greater than 6 [dB], calculate corrections to the signal level according to the following equation,

[2] The superscript coma indicates *in situ* measurements

$$L = 10\log\left(10^{L_{Sb}/10} - 10^{L_b/10}\right) \quad [\mathrm{dB}] \tag{2.8}$$

where L is the adjusted signal level, L_{Sb} is the level of signal and background noise combined and L_b is the background noise level, all quantities in [dB]. If the difference in levels is less than or equal to 6 [dB] in any of the frequency bands, is used the correction of 1.3 [dB] corresponding to a difference of 6 [dB].

2.3 Intensity method

Until the middle of the 70's the only acoustical quantity that could be measured accurately was the sound pressure. The amplitude part of sound pressure is a scalar quantity, which gives no information about the direction and the magnitude of the energy flow.

Sound intensity I [W/m^2] is a vector quantity, which describes the sound power per unit area. It is defined as the product of the sound pressure [Pa] and the particle velocity u [m/s], which is a vector quantity. The first instruments to measure the sound intensity in a wide frequency range where developed in the middle of the 70's. A full review of the theory and applications of the intensity method was presented by Fahy [4], who was also one of the first pioneers in this issue. Development of Fast Fourier Transforms analyzers, digital technology and acoustic transducers enable the direct measurement of sound intensity. Commercial equipment was become available in the beginning of the 80's; simultaneously appear the first papers of the two-microphone intensity method.

The two microphone p-p probe is the most usual method to determine a component of the particle velocity u. Time average particle velocity in any direction is determined by the time average pressure gradient between two microphones using Euler's equation. For the x direction becomes:

$$u_x = \frac{1}{\rho_o \Delta r}\int (p_B - p_A)dt \tag{2.9}$$

Where Δr [m] is the distance between the two microphones of the p-p probe, t [s] is the time and p_A and p_B are the pressure sensed by the microphones A and B, respectively. Thus, the phase information contained in the pressure signal is utilized in the intensity technique. To calculate the intensity, the pressure is determined by the average of the two microphone signals at the acoustical center of the probe, by:

$$p = \frac{p_A + p_B}{2} \tag{2.10}$$

The instantaneous intensity component I_n is approximated by:

$$I_n(t) \approx \left(\frac{1}{2\rho_0 \Delta r}\right)(p_A(t) + p_B(t))\int_{-\infty}^{t}(p_A(t) - p_B(t))dt \tag{2.11}$$

The distance between the two microphones is usually set at 6, 12 or 50 [mm], depending on the frequency range of interest in a p-p probe. The main assumption is that the inherent phase difference between the microphones is negligible. This is realized selecting two microphones from the production line, which have a phase response as similar as possible (phase matched microphones).

In practice there are always some mismatch phase difference between the two microphones and the channels of the analyzer, so a small residual intensity index δ_{pI_0} IEC 1043 [5] is determined as the difference between the pressure level and intensity level when both microphones are exposed to the same sound pressure (phase and amplitude), This factor is determinate at the calibration process.

$$\delta_{pI_0} = L_{p_0} - L_{|I|_0} \quad [dB] \tag{2.12}$$

The validity of the sound intensity measurement is described by the pressure intensity indicator, δ_{pI_0} or F_{pI} at each position:

$$F_{pI} = L_p - L_{|I|} \quad [dB] \tag{2.13}$$

Where $L_{/I/}$ [dB *re*1pW] and L_p are the average sound intensity level and the average sound pressure level at the measurement position, respectively.

The value of F_{pI} is zero only in a free field condition for a propagating plane wave, (the exact value is F_{pI}=0,1 [dB] because of the chain measurement, like cables, connections and to equipment it self). The value of F_{pI} increases with increasing sound reflections. In practical reverberant measurements, F_{pI} is usually larger than 3 [dB].

It is essential to keep F_{pI} smaller than δ_{pI_0} during acoustical measurements. In order to guarantee the measured intensity is not excessively biased by the residual intensity. The following criteria must apply:

$$F_{pI} < L_d = \delta_{pI_0} - K \quad [dB] \tag{2.14}$$

Where L_d is the dynamic capability index of intensity measurement instrumentation system and K [dB] is the bias error factor. When K=10, the accuracy of intensity measurements is better than 0,5 [dB], when K=7, the accuracy is better than 1.0 [dB].

The accuracy requirements for sound intensity probes are determined in IEC 1043, which gives the minimum values for δ_{pI_0} and are within 10 to 17 [dB] for a 12 [mm] microphone spacer. The higher values of δ_{pI_0} in commercial probes [6] are within 20 and 30 [dB], when the 12 [mm] microphone spacer is used.

The main application of the intensity method was the direct determination of sound power. The measurement of one component of the vector intensity is usually adequate because the determination of the sound power only needs the intensity component, normal to a hypothetic surface that encloses the sound source. The vector nature of intensity is lost because the orientation of the probe is not fixed.

The intensity method found is first application on building acoustics in 1980, where was determined the sound transmission loss of panels. The incident sound power was determined using the pressure method, but the transmitted sound power was determined directly in the vicinity of the test wall, by:

$$W_2 = \sum \overrightarrow{I} \cdot S \cdot \vec{n} \tag{2.15}$$

And the intensity sound reduction index R_I [3] could be determined by:

$$R_I = L_{p1} - L_{I2} - 6 \quad [\mathrm{dB}] \tag{2.16}$$

Where, the L_I is the time spatial and time average sound intensity level in the vicinity of the test wall or specimen, typically at a distance of 10 to 30 [cm].

The first international building acoustical measurement standard with possible application of the intensity method was published in 1995 as EN ISO 140-5 [7] Annex E, as a supplementary tool for façade measurements. The laboratory standard measurements method appears in 1999 as EN ISO 15186-1 [8].

[3] The subscript I, indicates that the Sound Reduction Index *R*, is obtained by intensity method.

F_{pI} is the most significant indicator of the validity of sound intensity measurements. According to EN ISO 15186-1 [8], F_{pI} should be smaller than 10 [dB]. This recommendation is based on investigations [9] that verified the R_I was affected by less than 1 [dB]. This limit is on disagreeing with eq. (2.14), which is also applied in EN ISO 9614 [10; 11].

The most serious problem with intensity measurements is that is not possible to accurately measured specimens which are sound-absorbing on the receiving room side. If the absorption coefficient of the specimen on the receiving room side is zero, which is the ideal case, the net intensity caused by extraneous noise, (e.g. flanking sound, reverberant direct sound, and background noise) is zero [12]. A sound absorbing specimen leads to underestimation of the true intensity radiated by the specimen if the intensity of the extraneous noise is sufficiently high. Thus, the R_I will be overestimated. If possible, the sound absorbing side should be towards the source room.

Hongisto [13] has study the difference between the maximum sound reduction indices obtained by the intensity method and by the pressure method and the influence of adding room absorption to the receiving room. The results obtained showed that it is possible to measure wall structures having better sound reduction index, using the intensity method that with the pressure method. This facilitates the measurements of small and/or heavy specimen in the presence of flanking.

2.3.1 Measurement of average sound intensity level on the receiving room

To measure the average sound intensity level on the receiving side, is used the scanning method for the building element under test and is defined a measurement surface that totally encloses this element, the area could be formed with a number of smaller sub-areas. The measurement surface is a plane parallel to the wall.

The measured distance related to the center of the microphone pairs and the wall is between 0.1 and 0.3 [m]. Avoid measured distance shorter than 0.1 [m] because of the near field of the vibrating element, the near field tend to change the sign of the intensity measurement rapidly with position.

The measurement surfaces should be chosen so that the measurement volume does not contain sound absorbing material that is not part of specimen under test (e.g. thick carpet). If this is not possible, then these absorbing surfaces shall be shielded with material having an absorption coefficient of less than 0.1 in each of the one-third octave bands for which the test will be conducted. Failure in shielding these surfaces can result in an underestimation of the radiated intensity and an overestimation of the apparent intensity sound-reduction index.

The position of the probe shall be normal to the measurement surface and the normal sound intensity shall be positive for energy flowing from the surface under test.

2.3.2 Scanning procedure

The scanning of each area or sub-areas is proportional to the size of the area, the speed must be kept constant, between 0.1 and 0.3 [m/s]. The change between sub-areas is always interrupted and saved.

The scanning of the areas or sub-areas is using parallel lines (horizontal and vertical scanning) turning at each edge. The density of the lines depends on the uniformity of the sound radiation. Non uniform radiation requires a more density lines. Normally is selected a distance between adjacent lines equal to the distance to the measured surface.

Before star the measures is made an initial test that consists in scanning the surface in a diagonal line across the measured area, this measure must meet the requirements of the background noise and the eq. (2.14).

The repeatability of the intensity measure is checked before the data may be used in computing the average intensity of the measured surface. Once the initial test is passed, the requirements of the eq. (2.14) must apply to both scans after recorded and computed, for all third-octave bands. The difference between scans must verify the following equation:

$$\left|\overline{L}_{In1} - \overline{L}_{In2}\right| \leq 1{,}0 \quad [\mathrm{dB}] \tag{2.17}$$

If the both criterions are verified, then the area intensity is given by the arithmetic average of the two scan measurements

$$\overline{L}_{In} = \frac{1}{2}\left(\overline{L}_{In1} - \overline{L}_{In2}\right) \quad [\mathrm{dB}] \tag{2.18}$$

If one of the criterions is not verified, repeat the two scans again. Change the scanning density or measurement environment variables to achieve the desired criterions and repeat the measures until the requirements are fulfilled.

2.3.3 Apparent intensity sound reduction index

The apparent intensity sound reduction index *in situ* is calculated by the equation (2.19),

$$R'_I = \left[L_{P1} - 6 + 10\lg\left(\frac{S}{S_0}\right)\right] - \left[\overline{L}_{In} + 10\lg\left(\frac{S_M}{S_0}\right)\right] \quad [\mathrm{dB}] \tag{2.19}$$

where the first term relates to the incident sound powering the source room and the second term relates to the sound power radiated from the building element in study within the measurement volume to the receiving room. L_{P1} is the average sound pressure level in the source room; S is the area of the separating building element under test; $\overline{L}_{In}$ is the average normal sound intensity level over the measurement surface in the receiving room; S_M is the total area of the measurement surface.

2.4 Pressure method versus Intensity method

Advantages of the intensity method are significant compared with the pressure method. A general comparison is presented on Table 2.1. The main advantage was that no special reverberant receiving room is needed and that the measurement of the receiving room absorption was avoided. The second advantage was that the intensity radiated by different parts of the panel could be determined separately. So far, vibration measurements on separate parts of specimen were used. Because the radiation factor of specimens is not well known below the critical frequency, the true radiated airborne sound intensity of a panel could not be reliably determined from vibration measurements. The third advantage is that the intensity method could be applied for determining the flanking sound power from room surfaces other than the separation partition.

Table 2.1 Advantages (+) and disadvantages (-) of pressure method versus intensity method in determining the sound insulation.

Pressure method	*Intensity method*
+ Fast and simple	- time consuming (more in point measures)
+ well known	- several intensity indicators
- isolated test rooms are necessary	+ isolation of test rooms less needed
- two reverberant rooms needed	+ One reverberation room is sufficient
- to measured heavy structures	+ small test specimen can be measured
- larger uncertainly	+ smaller uncertainly
	+ faster in scanning procedure
	+ enables determination of flanking paths
	+ reverberation time not needed
	+ point method enables sound localization
	- sound intensity calibration needed
	- expensive equipment
	- sound absorbing specimen prohibited (lab)

The disadvantages of the intensity method are the measurement technique places more stringent demands on the users and the equipment. The measurement time is dependent on the specimen size. When discrete points are used, the measurement times could be several hours for a 10 [m^2] surface. The determination of the δ_{pI_0} has to be performed before each measurement to assure that the phase-matching of the equipment is adequate.

Usually the results obtained with the intensity method were in good agreement, within 2 [dB] [12], with the pressure method. Typically, the intensity method yielded smaller values of R_I at low frequencies and higher values of R_I at high frequencies, than the pressure method.

The Waterhouse correction was suggested to be used to modify the results obtained by the intensity method closer to the results obtained by the pressure method. This correction is important, 1 to 3 [dB], at the lowest frequency bands. However, some authors propose that the intensity method gives the correct estimate of the R_I and the Waterhouse correction should be made to the results obtained with the pressure method. For now, the pressure method is more popular and the results of the intensity method more correct.

It is well known that the uncertainly of sound measurement using the pressure method is large at low frequencies, because the transmission room is small compared to the wavelength. With the intensity method, only incident sound power W_I is determined indirectly using eq. (2.2), while the transmitted sound power is measured directly. This leads to smaller uncertainly of the intensity method. The intensity method yields results more close to the true value of the R.

Pedersen [14] introduces a new method, which enables precision measurements at low frequencies, 50 to 160 [Hz], using pressure method in laboratory conditions.

Machimbarrena [15] showed that the differences between the pressure method and the intensity method can be smaller than 1 [dB], in the frequency range of 50 to 10 [kHz]. It is presupposed that the measurements were carried out in large test rooms and using adequate intensity measurement equipment (recent models of intensity analyzers and probes). They used only a 12 [mm] microphone spacer. The intensity analyzer was equipped with the possibility to improve the residual pressure-intensity index by correcting for phase mismatch.

2.5 Flanking transmission

The estimated *R* of wall structures depends on the test size. Firstly, values in the laboratory and *in situ* do not agree. Secondly, values between different laboratories do not agree. The main reason for different results is the different flanking condition. Structural sound transmission paths could vary too much, typically 3 to 10 [dB] differences are obtained.

The essential differences between laboratory and field tests are that, the quantity to be measured is not the same. In laboratory conditions, the direct transmission through the test specimen is the most interesting. This is usually arranged by isolating the rooms from each other so that the excitation of the receiving room is only the specimen surface. Therefore, flanking is usually stronger *in situ* than in laboratory measurements, leading lower values of the *R* *in situ*. Additionally, the test specimen, has is mounted in laboratory, as different coupling loss factors, different from *in situ* conditions.

In field conditions, flanking transmission is usually stronger than direct transmission, e.g. the difference between the sound power radiated by the partition and other surfaces is larger than 3 [dB]. Therefore, modeling of flanking is probably the main issue of current building acoustics. There is the need of design the appropriate structural solutions *in situ* using the *R* data obtained in laboratory conditions. Also this implies the proper verification *in situ* methods, which the recent draft of EN-ISO/FDIS 15186-2 [16] is the latest improvement.

2.6 The critical frequency

In this point, it is given a general and simple overview of the critical frequency and his mathematical formulation [17, 18, 20].

The transmission of oblique-incident sound through infinite plane plates can be formulated either in terms of shear and compressional waves, where the bending of the plate is considered as a superposition of these two wave types, or by utilizing the bending wave equation of the plate.

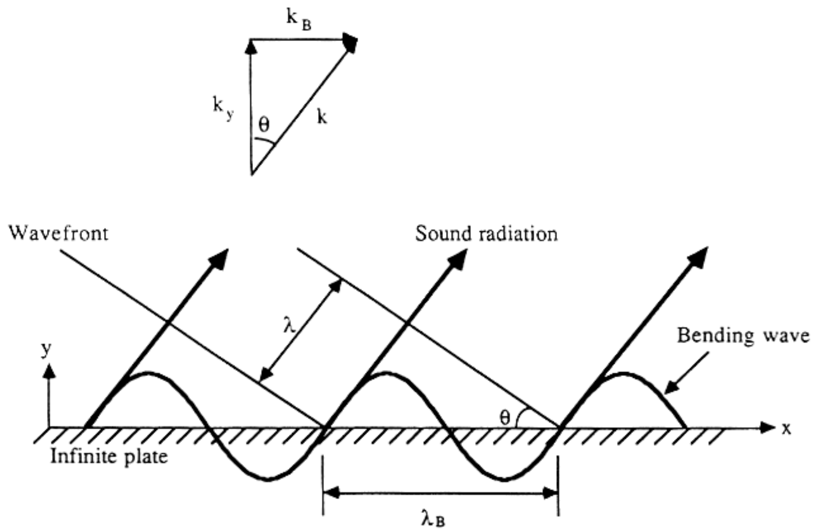

Figure 2.1 – Sound radiation from an infinite plate. [16]

When a plane sound wave is incident on the plate, at an oblique angle ϕ, (to the normal of the plate) that is smaller than the limiting angle ϕ_L

$$\phi_L = \arcsin\left(\frac{c_m}{c_b}\right) \tag{2.20}$$

Sound waves excite both longitudinal and shear waves in the plate material. This equation translates the connection between the velocity c_b of the bending waves established at the element (plate) and c_m denotes the sound velocity in the medium into which the sound is radiated. Which means that, only exist waves when $c_b \geq c$, has the value of sin ϕ_L, is between -1 and 1, therefore, when $c_b < c$, there is no sound radiation.

The critical frequency of the plate corresponds to the frequency value when both of propagation velocities (c_b and c) are equal.

Being the sound pressure related with the limit angle ϕ_L, the normal component of the bending velocity v_n, in a direction perpendicular to the plate, is calculated, by:

$$v_n = \frac{p}{\rho_0 c} \cos\phi_L \tag{2.21}$$

And the sound power radiated, by surface unit, is given by:

$$W = \sigma \rho_0 c v^2 \tag{2.22}$$

Where σ represents the radiation coefficient of the plate, which for free waves propagation is:

$$\sigma = \frac{1}{\sqrt{1 - \frac{f_{cr}}{f}}} \tag{2.23}$$

For homogeneous, isotropic and infinite plates the critical frequency is given by [18]:

$$f_{cr} = \frac{c^2}{2\pi}\sqrt{\frac{\rho_M h}{B}} \tag{2.24}$$

Where $\rho_M h$ [kg/m^2] is the surface f_{cr} mass and B [kNm^2/m] is the bending stiffness of the plate,

$$B = \frac{Eh^3}{(12(1-\nu^2))} \tag{2.25}$$

E is the Young Modulus and ν is the Poisson ratio of the material.

One may note that the critical frequency increases with increasing plate mass and decreasing with plate stiffness. If one express the ratio m/B in equation (2.24) in terms of the longitudinal wave velocity c_l in the plate material and the plate thickness h, then one finds that for homogenous plates [19].

$$f_{cr} = \frac{c^2}{1{,}8c_l h} \tag{2.26}$$

It can be seen, for $f<f_{cr}$ the expression (2.23) is not defined, so theoretically does not exist radiation. However, in practice, plates have finite dimensions, in this situation, the evolution of the radiation coefficient for free bending waves, can be given by Figure 2.2:

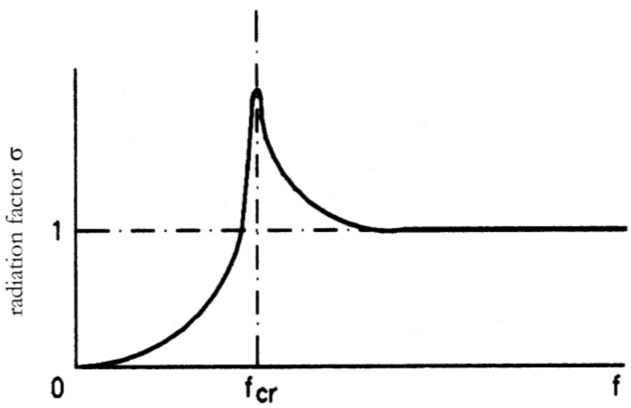

Figure 2.2 – Qualitative evolution of the radiation factor for bending waves in free regime [27].

In the case of homogeneous and isotropic wall elements (finite plates), the critical frequency corresponds to the frequency value associated with the intersection point of the curve, which is obtained by the bending wave number of the wall and the strait line corresponding to the wave number of the medium.

At this moment is necessary to clarify that the critical frequency is of most importance in the study of sound insulation between two dwellings and when there is the presence of flanking transmission. The application of the CEN model to lightweight double-leaf structures, studied by Nightingale [20] as noted that the adjoining structures can transmit sound only in structures bearing resonant vibration. Forced (non-resonant) vibration does not propagate across the structural joints. This means that flanking transmission can be significant only at frequencies above the critical frequency. The European model can predict well the behavior of double walls above the critical frequency. Below the critical frequency, the CEN model underestimates the transmission loss of the flanking path because the non-resonant vibration does not propagate between the rooms as the model presumes.

Other problem verified by Nightingale [20] is that in lightweight constructions the critical frequency is of very high frequencies 1000 to 2000 [Hz], compared with the critical frequency of the heaviest structures with frequencies in the range of 100 to 500 [Hz], which leads to an underestimation of the CEN model, in a frequency range that is in the "middle" of the building acoustics frequencies.

C a p i t u l o 3

Predicción del aislamiento acústico

En este capítulo se hace un resumen de dos métodos de predicción del aislamiento sonoro en edificaciones.

El punto 3.1 habla del modelo SEA que es un modelo estadístico de análisis de energía sonora que estudia la estimación de la energía sonora en distintos puntos de un edificio, transmitida tanto por vía aérea como estructural.

Se hace una descripción del método y artículos científicos donde se emplea este método.

En el punto 3.2 se habla del método de análisis modal, que es una herramienta para el estudio de cualquier sistema estructural y se aplica para estimar las características de la transmisión sonora entre particiones dentro de edificios.

Se hace referencia así mismo a aplicaciones prácticas de este método encontradas en artículos científicos.

C h a p t e r 3

3 - Prediction of sound insulation

3.1 The SEA model

The method called "Statistical Energy Analysis" – SEA, gives great opportunities to the estimation of sound energy, in several points of a building, transmitted by airborne or structural paths [21].

The mathematical model that supports this method consists in considering the building as a physical system and each dwelling and separating specimens as sub-systems of the physical system allowing in one hand, the interaction between sound fields in closed dwellings and by other hand, the transfer of the vibration mechanical energy by the elastic connections between several dwellings and the propagation of the energy through them selves.

To a given sub-system can be considerate, it is necessary that the geometric dimensions must be sufficient big in relation to the sound wave length, that pass through it.

Because this method is based on energetic balance between the various sub-systems in all building, sound power imputed must be equal to sound power dissipated, in steady conditions and for each sub-system. Thus, the building has, in each moment, total vibration energy which is distributed in all constituted sub-systems in a way that the transmitted sound summarizes on the energy transfer between the sub-systems in question.

If η_d is the dissipative internal factor of a given sub-system and E his sound energy verifies that the sound power dissipated at this sub-system P_d is equal to:

$$P_d = \omega\eta_d E \tag{3.1}$$

Thus, considering two sub-systems S_1 and S_2, with sound energy E_1 and E_2 ($E_1>E_2$), the sound power changed between them, will be:

$$P_{12} = \omega\eta_{12}E_1 - \omega\eta_{21}E_2 \tag{3.2}$$

Where η_{12} and η_{21} are the loss-coupling factors, related by the following expression:

$$n_1\eta_{12} = n_2\eta_{21} \tag{3.3}$$

Where, n_1 and n_2, are the modal density of the subsystem 1 and 2, respectively.

One of the main problem of the correct application of the method, begin in the definition of the sub-systems. Thus means, that these could be the separating elements or the volumes defined by them and in other cases the global eigen-modes of vibration.

Another reference is that, the SEA method uses his total (time and spatial average) vibrational energy as dynamic variable to estimate the response of each sub-system and his total vibrational (time and spatial average) energy. Beginning in the knowledge of the value of that energy, is possible to calculate all the values associated with the other dynamic variables (velocities, accelerations, displacements, on the separation element) namely referring to the sound pressure.

This method is of easy application, it needs few parameters for the possible amount of information and results that can give and it allows the characterization of the acoustic behavior of buildings.

At low frequencies, where there are few vibration nodes, this method has not reliable results and there are others inconvenients, when the degree of coupling between the sub-systems is considered low, it could present some difficulties to go on.

This prediction method is widely used in investigations of building acoustics in nowadays [22, 23, 24, 28].

Hopkins [24] used the SEA model results to compare with a flanking laboratory measurements for sound transmission across a separating and flanking cavity wall construction. The results obtained by the SEA model were in good agreement with the measured data, validating the SEA predictions for the direct and flanking transmission paths that are dominant.

Recent investigations by Nightingale [25] established expressions for the first order flanking path, derived using the SEA model. This expressions showed to be identical to the expressions appearing in EN ISO 12354-1 [26] for airborne sound insulation, even thought EN ISO 12354 was not derived using SEA.

3.2 The modal analysis method

The modal analysis method [27] is one of the most adequate tools to the study of any kind of structural system. It is applicable to estimate the characteristics of sound transmission in building partitions.

The response of these structural elements of a punctual excitation is tended to be dominated by the vibration modes that correspond to modal configurations which natural frequencies are in the range of the frequencies for the excitation force.

Modal configurations of the panels take the general form of contiguous regions of equal area and shape, which vary alternately in vibrational phase and are separated by nodal lines of zero vibration (Figure 3.1), changing in geometry and frequency with the boundary conditions.

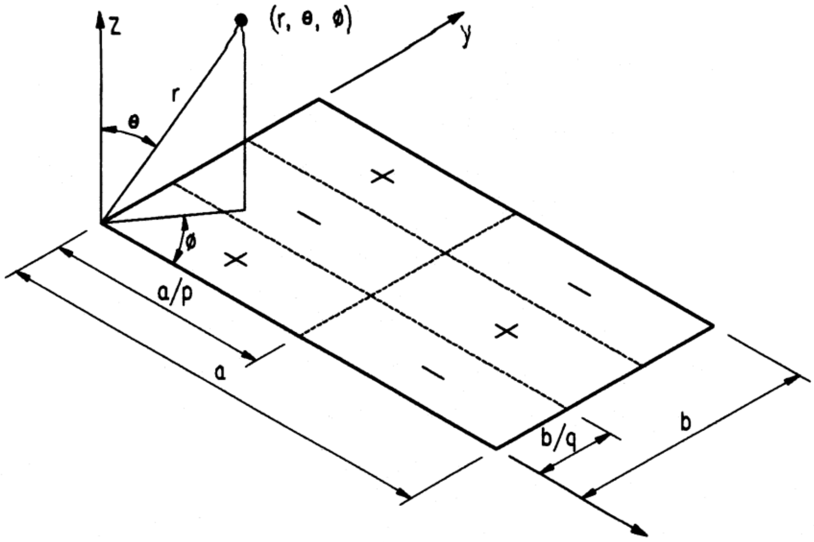

Figure 3.1 – Coordinate system, modal lines and phases of a vibrating rectangular panel.

Because of this, it is not correct to consider the same vibration nodes for the cases when the panel is totally isolated, simply supported or in some cantilever solution.

For rectangular panels with simply supported edges, the normal vibration velocity distribution is:

$$\bar{v}_n(x, y) = \bar{v}_{pq}\mathrm{sen}\left(\frac{p\pi x}{a}\right)\mathrm{sen}\left(\frac{q\pi y}{b}\right) \tag{3.4}$$

Where $0 \leq x \leq a$ and $0 \leq y \leq b$, and where p and q, represent natural numbers and $\bar{v}_{pq}$ is the vibration (time average) velocity complex amplitude for the vibration mode pq, where the angular frequency ω_{pq} is obtained by:

$$\omega_{pq} = \left(\frac{B}{m}\right)^{\frac{1}{2}}\left[\left(\frac{p\pi x}{a}\right)^2 + \left(\frac{q\pi y}{b}\right)^2\right] \tag{3.5}$$

Where *B* eq. (2.25), is the bending stiffness [kNm^2/m] and *m* [kg/m^2] the surface mass.

A measure of the velocity of vibration is the space-average value of the time average normal vibration velocity for the bending wave,

$$< \overline{v_n^2} >= \frac{1}{S}\int_s \left(\frac{1}{T}\int_0^{\pi} \overline{v_n^2}(x, y)dt\right)dS \tag{3.6}$$

where *T* is a suitable period of time over which, to estimate the mean square velocity at the point *(x,y)*, and *S* extends over the total vibrating surface, $< \overline{v_n^2} >$ is sometimes known as the "average mean square velocity". With this equation, we obtain the modal response for the natural frequency. For the determination of the time-average vibration energy and radiated power there are the following equations:

$$\overline{E} = \int_S m(x,y)\overline{v_n^2(x,y)}dS \quad \text{and} \quad \overline{W} = \eta\omega\overline{E} \tag{3.7}$$

Following the same procedure for the various modes (uncoupled between them), can be obtained the global modal response of the partition element.

This method can be applied, experimentally, using signal analyzing techniques or, analytically, using numerical methods appropriate for the determination of the natural frequencies.

In the determination of the modal radiation efficiency of these partition elements, the more efficiently procedure of determining the modal radiation efficiency, is exciting with a frequency identical or similar of the mode frequency, when is considered a one arbitrary excitation frequency.

Thus, is more usual to estimate the efficiency of radiation of the vibration modes that posses natural frequencies inside a range of frequencies, assuming a statistical distribution of the modal vibration energy (inside the frequency bandwidth).

With this analytic method it is possible to obtain more information quantity in relation to the dynamic behavior of the panel and because of it, to characterize his acoustical behavior. However, at high frequencies, where the modal density of the partition elements his very high and especially when the partition element to characterize has a big internal damping, which does not allow an easy identification of the natural vibration frequencies.

Patrício [28] has developed a simulation model for acoustic performance of non-homogeneous floors in structure-borne sound insulation. This model involves the modal approach analysis method for low frequencies and the SEA model for high frequencies. The results obtained by this model (program) were in good agreement with the *in situ* measured data.

Capitulo 4

Propósito del trabajo

El propósito de este trabajo es estudiar la aplicación de la técnica de intensimetría acústica en las mediciones del aislamiento sonoro *in situ* y se compara con las mediciones y resultados obtenidos por el método de presión. Para evaluar y cuantificar la transmisión por flancos en paredes simples se emplea la técnica intensimétrica. El trabajo se ha dedicado principalmente a evaluar el aislamiento sonoro entre particiones de edificios y después investigar y extender para el aislamiento a sonidos de impactos en las mismas condiciones.

C h a p t e r 4

4 - Purpose of this work

The purpose of this work is to study the application of the sound intensity technique to the measurement of sound insulation *in situ* and compare with the measurements and results made with the pressure method. To evaluate and to quantify the flanking transmission in simple wall structures, with the application of the intensity technique. The work was primarily to evaluate the airborne sound insulation between dwellings and further more, to investigate the impact sound isolation in the same conditions.

C a p i t u l o 5

Equipamiento, materiales y sitios

En este apartado se hace una descripción de todo el equipo utilizado en las medidas, así como los materiales de apoyo y los sitios donde se hicieron las medidas de intensidad y presión *in situ*.

El equipo utilizado es descrito según los métodos de medida, esto es, equipos para las medidas de presión (apartado 5.1.1) y equipos para las medidas de intensidad (apartado 5.1.2).

C h a p t e r 5

5 - Equipment, materials and places

All measured methods used in this work, are standardized and only *in situ* measures were made. The measurements were done in third-octave bands. The frequency range of concern was 100 to 4000 [Hz].

5.1 Measurement places

The *in situ* pressure and intensity measures were made in the same two dwellings of the University of Valladolid, “Facultad de Derecho”, which at the moment, was not in use for classes.

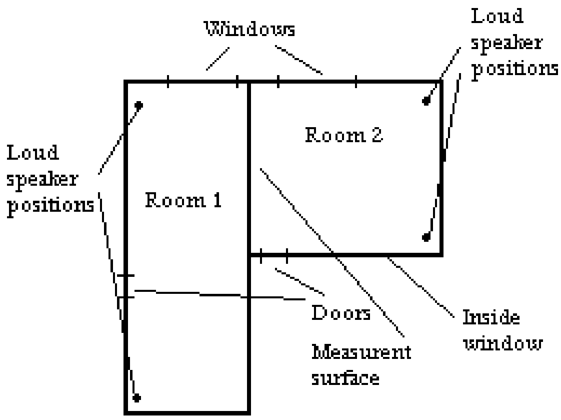

Figure 5.1 – Sketch of the measurement places room (1) and (2).

The room (1) has a volume of 68.8 [m^3] and the room (2) of 60 [m^3]. The partition element between the two rooms is supposed to be of a single leaf. Both rooms have wood doors and a aluminum alloy window with double structures and single glass. The room (2) has in one of the walls, an inside window with two glass leafs that covers all the top wall length in 80 [cm]. All the walls are finished with concrete and are painted and the floor of room (2) is covered with a carpet. The ceilings have the illumination settings.

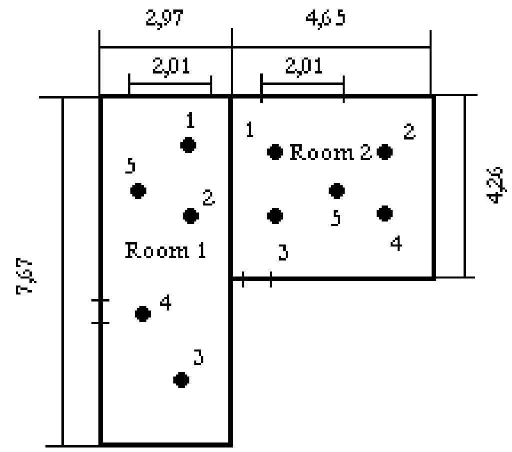

Figure 5.2 – Rooms dimensions and
microphone measurement positions in [m].

Figure 5.3 – Room (1) view, with loudspeaker
in position.

Figure 5.4 – Partial view of the room (2)

The dimensions of the room (1) in meters are, with of 2.97 and length of 7.67 [m].

The dimensions of room (2) are, with of 4.26 and length of 4.65 [m].

The high of both rooms is 3.03 [m].

5.1.1 Pressure method

The equipment used in this work was for the pressure measures, the dual-channel real time frequency analyzer B&K type 2144 and the sound source B&K type 4224, a sound level calibrator B&K type 4231 and a microphone B&K type 4190 of ½ inch with a frequency range of. 20 [Hz] to 20 [kHz], ± 1 [dB] and a polarization voltage of 200 [V]. The data was post-processed by the software B&K "Building acoustic program" WT9343 Ver.1.71 (1992).

5.1.2 Intensity method

For the intensity measures the same equipment was used as the pressure method and additionally the sound intensity p-p probe B&K type 3520 modified to a more recent model, with sound intensity microphone pairs B&K type 4181 of ½ inch with a frequency range of 20 [Hz] to 20 [kHz], ± 1 [dB] and a polarization voltage of 200 [V]. For the calibration procedure was used the sound intensity calibrator B&K type 3541.

Capitulo 6

Resultados

Los resultados que se presentan en este apartado están agrupados de acuerdo al método de medida empleado.

En el punto 6.1 se describen los trámites para medir presión según las normas ISO 140-4. Se miden ruidos de fundo, tiempos de reverberación y niveles de presión para la estimación de *R'* y para diferentes posiciones de la fuente de ruido. Los resultados se presentan en tablas y gráficas.

En el punto 6.2 se describen las medidas de intensidad según el borrador de norma ISO/FDIS 15186-2. Se presentan los valores del índice de intensidad residual, obtenidos durante la calibración y el nivel de reducción sonora R'_I.

En el punto 6.3 se hace una comparación de los resultados obtenidos por ambos los métodos (tabla 6.3 y figura 6.11).

La figura 6.12 es una comparación entre los dos métodos y con la corrección de Waterhouse.

En el punto 6.4 se hacen unas medidas *in situ* en la E.T.S.I.I. entre dos particiones del laboratorio de acústica, con el fin de verificar si los barridos entre medidas son repetibles, o sea, que la diferencia entre ellos sea inferior a 1 [dB] según el criterio de la ecuación 2.13.

C h a p t e r 6

6 - Results

6.1 Pressure Method

Measurements by pressure method were made using procedures of the EN ISO 10140-4 [2], to calculate reverberation time and apparent sound reduction index *R'*.(2.7) value W_3 is assumed to be not quantifiable and the summation of both W_2 and W_3 together was measured in both rooms and were made comparison between the results.

For each room, three different series of measures and calculations were made:

Background noise levels and correspond corrections (when necessary), with equation (2.8).

Reverberation time, using equation (2.4);

Pressure levels estimation of *R'*, obtained with equation (2.7).

Present results were done in the frequency range of 100 to 4000 [Hz], in third-octave bands. The following figures are printed from the software "Building Acoustic program" B&K WT9343 and are the results of the post-processed data.

6.1.1 First procedure: room 2 measures (receiving room)

The measures presented are when sound source is placed at room (1 - source room) and the microphone is positioned in room (2 – receiving room) see Figure 5.1. For the *R'* calculations, two different sound source positions were used. To each sound source position correspond 5 different measured microphone positions, as it can be seen in Figure 5.2, that is 10 measurements in total at each room. Mean values for L_{p1} and L_{p2} are shown at Figure 6.1, second column shows the pressure level at source room (1), third is the pressure level at receiving room (2). Sixth column shows the calculated value of *R'* following equations (2.5) and (2.7).

Reverberation time was measured in room (2) in 4 different microphone positions and with an exposed time of 6 seconds. The measured values are shown in the sixth column of Figure 6.1.

Background noise was measured with one microphone in only one position and in one room; it is supposed to be the same for both rooms. The measurement values are shown at fourth column in Figure 6.1.

Airborne Sound Insulation

Job Directory:
C:\DATA9343\CARLOS
File ID: CARLO1

Number of files in calc.

Source room ...... L1 : 10
Receiving room ... L2 : 10
Background noise . B2 : 1
Reverberation time T2 : 4

Freq. [Hz]	L1 [dB]	L2 [dB]	B2 [dB]	T2 [s]	R' [dB]	Dev. [dB]
100	84.00	52.2	25.4	----n	----	----
125	93.10	63.1	26.8	----o	----	----
160	89.30	56.8	21.6	----o	----	----
200	89.60	59.7	24.1	----o	----	----
250	92.00	57.2	20.2	----o	----	----
315	93.60	58.5	18.0	2.51	40.6	----
400	95.50	59.0	19.0	1.87	40.7	----
500	97.10	60.5	18.3	1.62	40.2	----
630	98.00	61.4	14.9	1.45	39.6	----
800	93.90	56.8	12.6	1.32	39.7	----
1000	91.10	48.3	12.2	1.25	45.2	----
1250	92.40	45.8	12.7	1.23	48.9	----
1600	94.80	45.8	12.7	1.05	50.6	----
2000	92.90	39.8	10.6	0.99	54.5	----
2500	90.80	35.5	11.5	1.00	56.8	----
3150	82.70	25.1	7.3	0.94	58.8	----
4000	84.60	24.0	6.1	0.97	61.8	----

Figure 6.1 – Values for: source room L1; receiving room L2; background noise B2 and reverberation time T2.

Values presented with the number "o" could not been measured, because the background noise was too loud at low frequencies, which unable to measure reverberation time at low frequencies, 100 to 250 [Hz].

Figure 6.3 shows the graphical representation of three measures and calculated *R'* for the test specimen in the direction of room (1) to room (2).

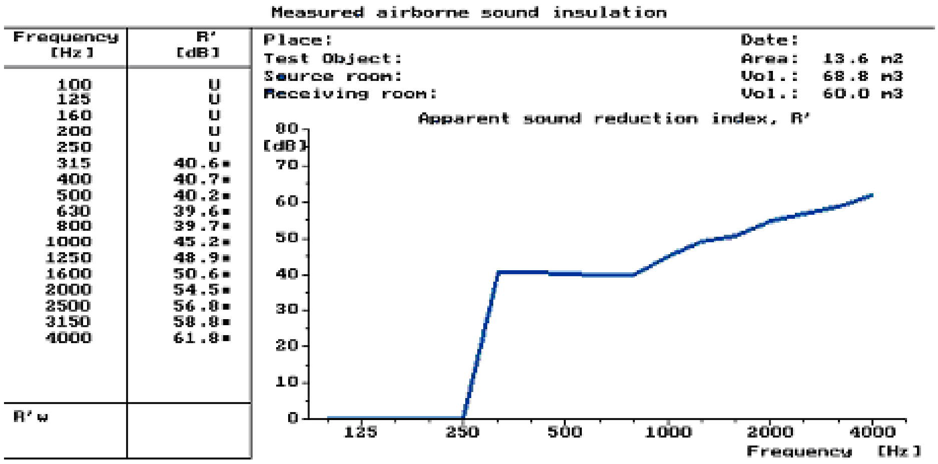

Figure 6.2 – Apparent sound reduction index *R'* from source room (1) to receiving room (2).

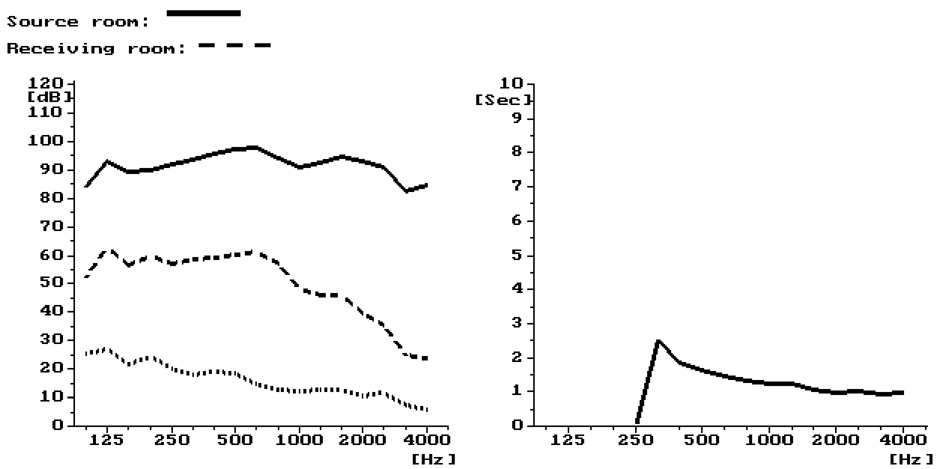

Figure 6.3 – Left figure illustrates the source room pressure level L1, the receiving room pressure level L2 and the background noise B2 (top to bottom). The right figure shows the reverberation time for the room (2).

6.1.2 Second procedure: room 1 measures (receiving room)

At this case sound source is placed in room (2) and microphone is positioned at room (1). Measurements are made in both sound source positions in room (2) giving a total of 10 archives or measured positions. This measure used 5 different positions to measure the reverberation time. The exposed time was, in this case of 7 seconds.

Airborne Sound Insulation

Job Directory:
C:\DATA9343\CARLOS2
File ID: CARLO2

Number of files in calc.

Source room ...... L1 : 10
Receiving room ... L2 : 10
Background noise . B2 : 1
Reverberation time T2 : 5

Freq. [Hz]	L1 [dB]	L2 [dB]	B2 [dB]	T2 [s]	R' [dB]	Dev. [dB]
100	83.80	54.2	24.9	----o	----	----
125	91.90	64.3	27.5	----o	----	----
160	87.20	57.9	28.0	----o	----	----
200	90.50	58.3	31.7	2.44	37.0	----
250	90.70	57.6	33.0	2.11	37.3	----
315	92.20	59.0	37.0	2.12	37.3	----
400	94.00	58.8	31.3	1.79	38.7	----
500	95.30	59.6	31.3	1.64	38.7	----
630	96.60	61.2	29.0	1.53	38.0	----
800	92.40	56.2	30.5	1.30	38.2	----
1000	88.50	48.3	28.4	1.34	42.3	----
1250	88.60	46.0	28.0	1.18	44.1	----
1600	90.40	45.3	31.2	1.08	46.3	----
2000	89.70	40.1	25.5	1.02	50.5	----
2500	87.90	36.3	21.9	0.91	52.1	----
3150	79.80	25.4	19.9B	0.92	56.2	----
4000	81.50	24.1	16.7b	0.93	58.8	----

Figure 6.4 - Values for: source room L2; receiving room L1; background noise B1 and reverberation time T1.

Measured airborne sound insulation

Frequency [Hz]	R' [dB]
100	U
125	U
160	U
200	37.0
250	37.3
315	37.3
400	38.7
500	38.7
630	38.0
800	38.2
1000	42.3
1250	44.1
1600	46.3
2000	50.5
2500	52.1
3150	56.2
4000	58.8
R'w	

Place: Date:
Test Object: Area: 13.6 m2
Source room: Vol.: 60.0 m3
Receiving room: Vol.: 68.8 m3

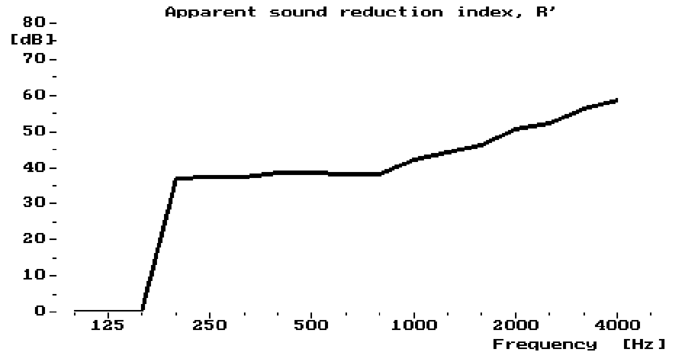

Figure 6.5 - Apparent sound reduction index *R'* from room (2) to room (1).

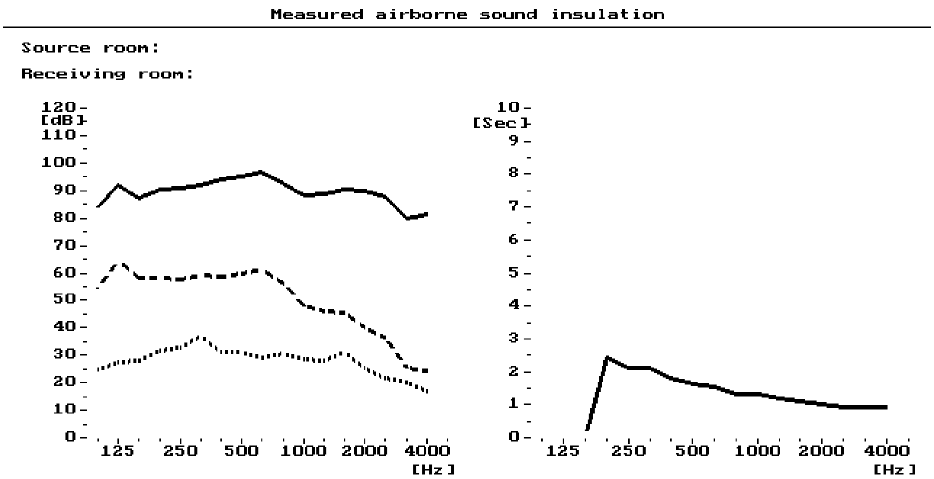

Figure 6.6 - Left figure illustrates the source room pressure level L2, the receiving room pressure level L1 and the background noise B1 (top to bottom). The right figure shows the reverberation time T1.

Measured airborne sound insulation

Result 1: Current result R'w = 0 dB Max.Unf.Dev = 0.0 dB at 25 Hz

Result 2: CARL0101.TXA R'w = 0 dB Max.Unf.Dev = 0.0 dB at 25 Hz

Freq. Hz	R'(1) [dB]	R'(2) [dB]	1-2 [dB]
100	-256.	-256.	0.0
125	-256.	-256.	0.0
160	-256.	-256.	0.0
200	37.0	-256.	293.0
250	37.3	-256.	293.3
315	37.3	40.6	-3.3
400	38.7	40.7	-2.1
500	38.7	40.2	-1.5
630	38.0	39.6	-1.6
800	38.2	39.7	-1.5
1000	42.3	45.2	-2.9
1250	44.1	48.9	-4.8
1600	46.3	50.6	-4.4
2000	50.5	54.5	-4.0
2500	52.1	56.8	-4.7
3150	56.2	58.8	-2.5
4000	58.8	61.8	-3.0

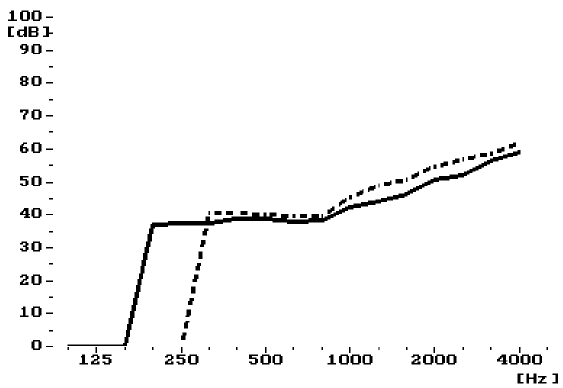

Figure 6.7 – The sound reduction index in the two directions.

Sound reduction index measured in both directions for the rooms in study, present values with a difference of the first measure values, upper than the values of the second measure, as it can be seen in the fourth column of the chart in Figure 6.7.

The values presented in Figure 6.7 on second column and third column with the value “-256” are out of range, as the consequent values.

6.2 Intensity Method

Intensity measurements were based using procedures of the EN ISO 9614-2 [11] and the draft ISO/FDIS 15186-2 [16].

6.2.1 Test and measurement procedure

For one loudspeaker position at room (1), was measure the average sound pressure level in the source room, L_{P1}, and the average sound intensity level on a measurement surface in the receiving room, L_{I2}. Measurement conditions must be satisfactory; this is verifying the Eq. (2.14) for K=7.

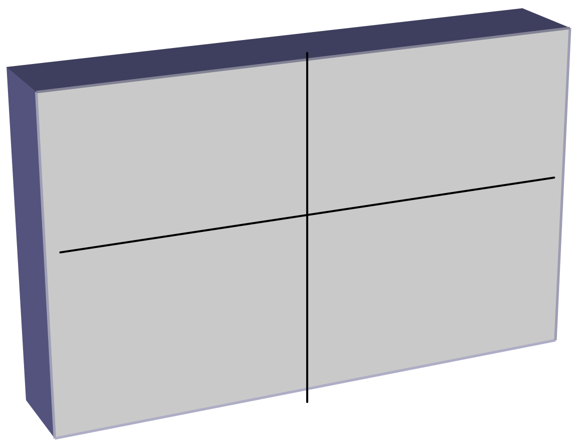

Figure 6.8 – Planar measurement surface of room (2) composed from 4 sub-areas, all of which parallel to the building element under test

Sound field is generated by a sound source as the requirements of ISO 140-4 [2].

Residual intensity index δ_{pI_0} is obtained at the calibration process. This procedure is always performed before each new measurement.

Table 6.1 – Residual intensity index in [dB] at calibration.

Freq.	100	125	160	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
δ_{k0}	11	13	14	15	16	16	17	17	17	17	17	18	19	18	18	19

The measurement time of scan patterns was of 19 minutes each, giving a velocity of approximately 0.12 [m/s].

The following Figure 6.9 shows sound reduction index for intensity method, without the Waterhouse correction K_c.

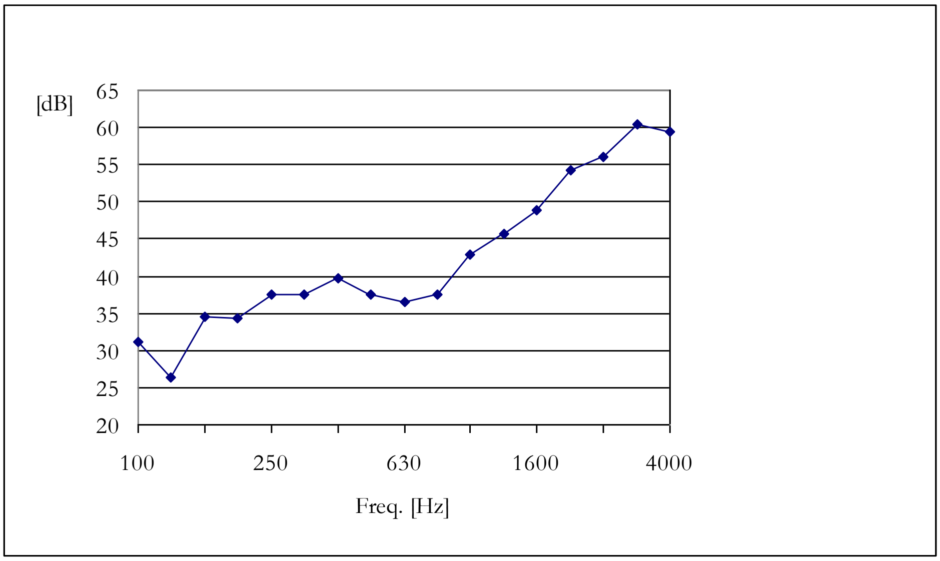

Figure 6.9 – Chart of apparent sound reduction index R' by ISO 15186-2

Figure 6.10 – Partial view of room (2) in sound intensity measurements.

6.3 Compared results

Intensity measurement that was compared with the pressure method was the measurement of the partition wall that separates the two dwellings. The table that expresses measures and their few reliability numbers are presented in Table 6.2.

Shaded values shown on table are those that are valid for the requirements of ISO/FDIS 15186-2 [16].

Table 6.2 – Intensity values and associated errors at the measure

Freq.	L_{p1}	Scan 1	Scan 2	Control and average value	$I_{eq(average}$	$\delta_k<\delta_{k0}$-7	R'_I
	[dB]	[dB]	[dB]	Δ<1	[dB]	[dB]	[dB]
100	84,0	50,7	43,1	7,6	46,9	16,9	31
125	93,1	60,8	60,7	Ok	60,7	5,7	26
160	89,3	49,2	48,4	Ok	48,8	5,6	35
200	89,6	49,9	48,5	1,3	49,2	4,8	34
250	92,0	49,0	47,7	1,3	48,4	4,4	38
315	93,6	50,3	49,7	Ok	50,0	3,9	38
400	95,5	50,4	49,1	1,3	49,7	5,0	40
500	97,1	53,9	53,4	Ok	53,6	1,7	37
630	98,0	55,7	55,4	Ok	55,6	0,5	36
800	93,9	50,7	50,2	Ok	50,4	Ok	37
1000	91,1	42,5	41,9	Ok	42,2	Ok	43
1250	92,4	41,1	40,4	Ok	40,7	Ok	46
1600	94,8	40,2	39,5	Ok	39,8	Ok	49
2000	92,9	33,5	31,9	1,6	32,7	Ok	54
2500	90,8	29,2	28,3	Ok	28,8	Ok	56
3150	82,7	14,9	17,5	-2,5	16,2	2,7	61
4000	84,6	20,2	18,1	2,1	19,1	Ok	59

As it can be seen in the following Figure 6.11 and Table 6.3 difference between the two methods is inside a range of 3 [dB] maximal.

Table 6.3 shows values of both methods and difference obtained by the two sound reduction indexes.

Table 6.3 – Values of Sound reduction index for the two measurement methods and respectively differences

Freq. [Hz]	R' [dB] ISO 140-4	R_i' [dB] ISO/FDIS 15186-2	Difference [dB]
315	41	38	-3,0
400	41	40	-0,9
500	40	37	-2,7
630	40	36	-3,2
800	40	37	-2,2
1000	45	43	-2,3
1250	49	46	-3,2
1600	51	49	-1,6
2000	55	54	-0,3
2500	57	56	-0,8
3150	59	61	1,7
4000	62	59	-2,3

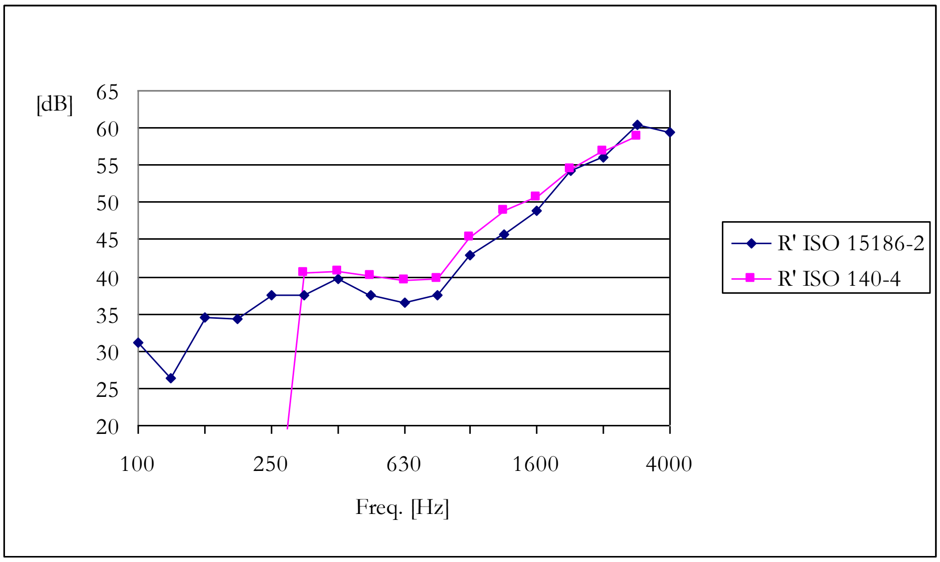

Figure 6.11 – Chart comparison of the two sound reduction indexes, ISO 140-4 and ISO/FDIS 15186-2

These values could be corrected with the correction K_c proposed by annex A of the draft ISO/FDIS 15186-2 Table 6.4.

Table 6.4 – Waterhouse correction values.

Frequency [Hz]	***K_c***	***Frequency [Hz]***	***K_c***	***Frequency [Hz]***	***K_c***
100	**2,1**	400	**0,6**	1600	**0,3**
125	**1,7**	500	**0,5**	2000	**0,2**
160	**1,4**	630	**0,4**	2500	**0,2**
200	**1,2**	800	**0,3**	3150	**0,1**
250	**1,0**	1000	**0,3**	4000	**0,1**
315	**0,8**	1250	**0,2**	5000	**0,1**

Figure 6.12 shows values for ISO/FDIS 15186-2 with the Waterhouse correction and it can be seen that the correction is visible at low frequencies where there are no measurements values for ISO 140-4 method, which is impossible to take conclusions.

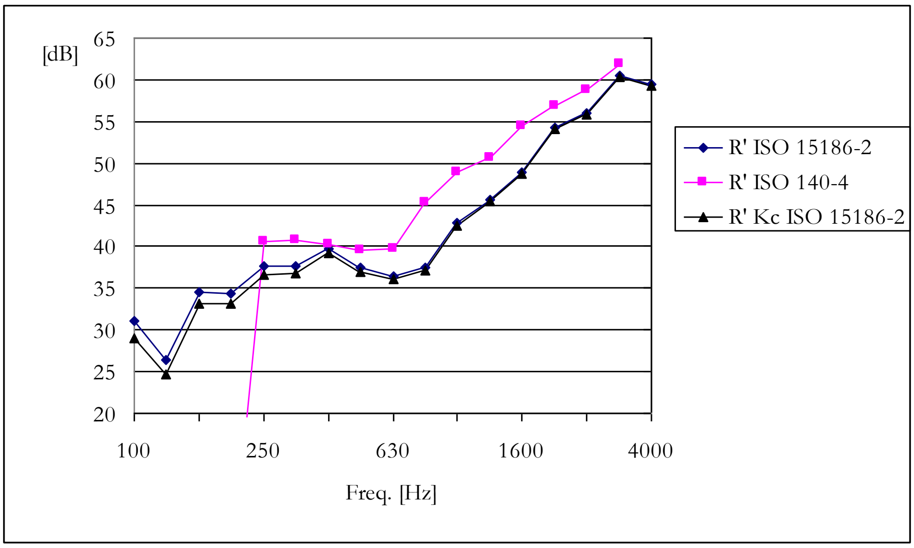

Figure 6.12 - Chart comparison of the three sound reduction indexes, ISO 140-4 and ISO 15186-2 and ISO 15186 with K_c.

6.4 Experiences to evaluate errors in measurement procedure

To achieve possible causes of the unachieved criteria, Equations (2.13) and (2.16) of the intensity procedure verified in field measurements, were made two different experiences at the university laboratory. Experiences were performed between two dwellings and the separating surface studied was the surface door between them. Dimensions of the dwellings are expressed in meters in the Figure 6.13. All laboratory furniture was maintained and in the same position.

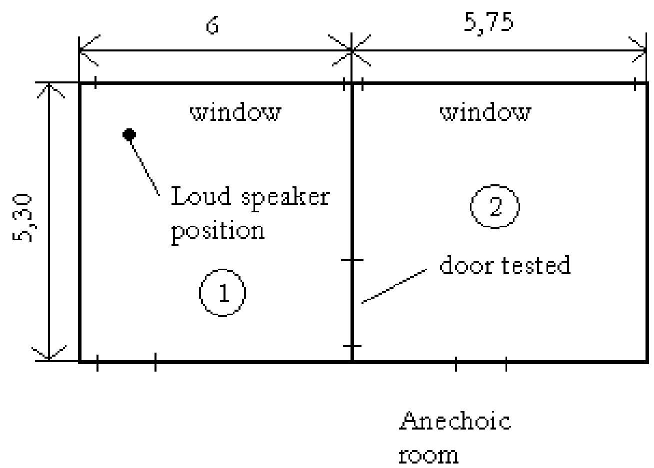

Figure 6.13Rooms dimensions and loud speaker position.

Dimensions of the tested door are 1,50x2,08 [m].

Firstly were chosen two variables in the measurement procedure, probe velocity displacement and distance to the surface in study.

In experience 1 was used the same velocity (approximately) that was used on field and was changed the distance to the surface test. In this case changed to 5 to 10 [cm] (before was of 15 to 20 cm).

In experience 2 was used a distance of 15 to 20 [cm] and the probe velocity changed to approximately to half of the initial values. Is said the double of measurement time.

Figure 6.14 View of the tested door.

As it can be seen in Table 6.5 there are no significant improve results in this change of experience 1 in measurement procedure, the mean value of the difference between scans is of 4,85 [dB], this value is calculated with summation of all values out of range for all frequencies (values inside the range are not summarized). Although the 4th column present for all frequency values the validation of equation (2.13).

Table 6.5 Intensity scans values of experience 1 and associated errors.

Freq.	Scan 1 [dB]	Scan 2 [dB]	Control and average value $\Delta<1$	$\delta_k<\delta_{k0}-7$ [dB]
100	74,43	72,44	1,99	Ok
125	78,13	72,67	5,46	Ok
160	73,87	71,89	1,98	Ok
200	72,25	68,7	3,55	Ok
250	72,15	67,64	4,51	Ok
315	69,68	66,3	3,38	Ok
400	74,93	66,11	8,82	Ok
500	76,5	66,49	10,01	Ok
630	79,4	73,16	6,24	Ok
800	72,95	67,78	5,17	Ok
1000	69,33	66,51	2,82	Ok
1250	70,37	66,72	3,65	Ok
1600	73,28	67,68	5,60	Ok
2000	73,59	69,05	4,54	Ok
2500	70,79	66,3	4,49	Ok
3150	64,58	60,46	4,12	Ok
4000	66,18	60,14	6,04	Ok

In Table 6.6 the same mean value between scans is now of 2,49 [dB] which is about half of experience 1 and present 3 frequencies (125, 160 and 630 Hz) that are in the interval of error, that is lower than 1 [dB].

These experiences lead to two conclusions, that the measurement velocity is of most importance, must be very similar between measurements and must have an absolute value less or equal than 0,10 [m/s] and the presence of furniture improve reverberation time. Results of the pressure-intensity indicator F_{pI} smaller than the residual intensity index δ_{pI_0} (column 4th values) are all inside the range for both experiences made at the acoustical laboratory.

Table 6.6 Intensity scans values of experience 2 and associated errors.

	Scan 1	Scan 2	Control and average value	$\delta_k<\delta_{k0}$-7
Freq.	*[dB]*	*[dB]*	*Δ<1*	*[dB]*
100	68,72	71,07	-2,35	Ok
125	70,6	70,86	Ok	Ok
160	69,94	70,32	Ok	Ok
200	63,57	67,66	-4,09	Ok
250	67,99	67	Ok	Ok
315	71,07	66,01	5,06	Ok
400	72,44	63,99	8,45	Ok
500	72,32	64,93	7,39	Ok
630	71,99	73,02	Ok	Ok
800	67,33	65,69	1,64	Ok
1000	63,85	62,44	1,41	Ok
1250	66,18	62,75	3,43	Ok
1600	68,72	65,24	3,48	Ok
2000	68,37	66,51	1,86	Ok
2500	66,01	64,06	1,95	Ok
3150	59,22	58,04	1,18	Ok
4000	61,95	59,03	2,92	Ok

C a p i t u l o 7

Discusión

Cuando se mide de acuerdo al método de presión (ISO 140-4), en ambos sentidos posibles (sala emisora convertida en receptora y viceversa), se obtiene una excelente concordancia en los resultados, tal y como se puede ver en la Figure 6.7.

Para el método de intensidad, las medidas efectuadas en la Facultad de derecho, no pudieron ser consideradas validas, porque los requerimientos para validar las medidas no pudieron ser cumplidos.

Se han realizado otros experimentos en el laboratorio de acústica con el fin de llegar a una posible explicación para los errores que causaron las diferencias en las medidas intensimétricas. En este caso los resultados fueron mejores pues el criterio de la ecuación (2.13) para K=7 se cumplía. Es posible que la razón de la mejora fuese la presencia de los muebles del laboratorio ya que reduce la reverberación de la sala. En futuros experimentos, mejorando el tiempo de reverberación en la sala receptora es posible alcanzar el criterio de la ecuación (2.13) El criterio de la ecuación (2.16) es posible de alcanzar con diferentes experimentos, cambiando el nivel de la presión sonora en la sala emisora. Buscando el nivel de presión adecuado en la sala receptora, reduciendo los ruidos extraños medidos por la sonda de intensidad, puede llevar a mejores resultados entre los barridos. Esta conclusión, está fundamentada con la experiencia 1, donde la sonda de intensidad esta colocada más cerca de la superficie de medida, revelando (tercer columna de la Table 6.5 valores extremamente elevados.

Los únicos valores de intensidad de las medidas *in situ* que se presentan en este trabajo, tienen pocos errores comparados con las medidas de otras superficies y que fueron usadas para llegar a algunos de sus objetivos.

Analizando la gráfica de la Figure 6.11 se observa una forma muy similar de las dos líneas. Los valores presentados por las medidas de intensidad son solamente para la pared de separación y su índice de reducción sonora.

Las diferencias pueden representar potencia sonora adicional debida a la contribución de las transmisiones de flanco.

Chapter 7

7 – Discussion

Pressure measurement procedure made in the two directions of the dwellings present values with very good agreement as it can be seen in Figure 6.7.

For intensity method, measurements made at the "Facultad de Derecho" could not be considered valid, because the requirements to validate measures could not be fulfilled.

Other experiences were made at the acoustical laboratory to attempt achieve a possible explication to the error that causes the mismatch in the measures. These measurements present better results, criteria of equation (2.13) for K=7 was accomplished and the possible cause was the maintenance of the furniture. In future experiences improving reverberation time (with additional absorption material) at receiving room is possible to achieve the criteria of equation (2.13). The criteria of equation (2.16) is possible to achieve with different experiences, changing sound pressure level at source room. Finding a proper sound level in the receiving room, reducing the extraneous noises measured by the intensity probe could lead to better results between scans. This conclusion is based in experience 1, where intensity probe is positioned closer to the surface specimen, showing (3rd column of Table 6.5) values extremely high.

The only intensity values of field measures that are present in this work, have few errors compared to the other surface measures and were used too accomplished some of his objectives.

Analyzing the chart showed in Figure 6.11 present a very similar draw of both lines. The values presented by intensity measures are only for the separating wall and his sound reduction index.

The differences could represent additional sound power contributed by the flanking transmission presented in other walls of the room.

Their contribution could not be evaluated has expected. Measures made in others rooms surfaces presented values that could not been treated for this study, because imply new measures that could not been done in time and measurement places have already suffer building changes due to other investigations works

In future measurements with intensity method it will be expected to locate the possible cause of measurement errors and then complete the study.

NOTATION

A	boundary length of the plate in x direction
A_2	room absorption area of the receiving room
B	bending stiffness of the plate
B	boundary length of the plate in y direction
c_m	velocity of the bending wave in the medium
C	sound velocity on the fluid
c_0	velocity of the sound in air
c_b	velocity of the bending wave at the plate
c_l	longitudinal wave velocity at the<plate
$\delta_{pI,0}$	residual intensity index
Δr	distance between two microphones in the p-p probe
E	Young modulus; Energy of a sub-system
E_1	sound energy of sub-system 1
E_2	sound energy of sub-system 2
$\overline{\mathrm{E}}$	time average vibration energy
ϕ	incident angle of the wave
f	wave frequency
f_{cr}	critical frequency
ϕ_L	limit angle
FpI	pressure-intensity indicator

h	thickness of the plate
η_{21}	loss coupling factor
η_{12}	loss coupling factor
η_d	dissipative internal factor of a given sub-system
I	sound intensity
I_n	instantaneous intensity component
K	bias error factor
L_d	dynamic capability index of intensity measurement
L_I	time spatial and time average sound intensity level
L_p	average sound pressure level
L_{p1}	average sound pressure levels in the source room
L_{p2}	average sound pressure levels in the receiving room
L_{pI}	sound level, pressure-intensity indicator
ν	Poisson's ratio
n_1	modal density of sub-system 1
n_2	modal density of sub-system 2
p *and* q	natural numbers
P_1	sound pressure in the source room
P_2	sound pressure in the receiving room
p_A	pressure sensed by the microphone A of the p-p probe
p_B	pressure sensed by the microphone B of the p-p probe
P_d	sound power dissipated in a sub-system

p_{ref}	reference pressure
R	sound reduction index calculated with pressure method
R'	sound reduction index calculated *in situ*
ρ_0	density of air
R_I *and* R'_I	Sound reduction index calculated with intensity method in laboratory and *in situ* respectably.
S	area of the test specimen
σ	radiation coefficient of the plate
T	period of time
T_2	reverberant time of the receiving room
u	particle velocity
V_2	volume of the receiving room
v_n	normal component of the bending velocity
$\bar{v}_n$	normal vibration velocity distribution
$<\overline{v_n^2}>$	average mean square velocity
$\bar{v}_{pq}$	vibration (time average) velocity complex amplitude for the vibration mode *pq*
w	natural frequency
$\overline{W}$	time average radiated power
W_1	incident sound power on a partition under test
W_2	sound power transmitted through the separating element
W_3	sound power transmitted through flanking elements or by other components
ω_{pq}	angular frequency for the pq vibration mode
x	x direction in Cartesian referential

τ — transmission coefficient

MATHEMATICAL OPERATIONS

$| \; |$ — Modulus of

$\langle \; \rangle$ — Space-average

$\overline{}$ — Time-average

$\approx$ — Approximated

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